

The Nebulosity and Distance of the Cepheid RS Puppis

Michael W. Feast

Astronomy Dept, University of Cape Town, Rondebosch, 7701, South Africa
(email: mwf@artemisia.ast.uct.ac.za)

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ABSTRACT

Adopting a distance for RS Pup derived from a period-luminosity relation based on Cepheid parallaxes, it is shown that the phase-lag observations of the surrounding nebulosity by Kervella et al. are well fitted by a model of an equatorial disc at an angle of $8^\circ.1 \pm 0^\circ.6$ to the plane of the sky. The astrophysical implications of this are briefly mentioned.

Key words: Stars: individual: RS Pup, Stars: circumstellar matter, Stars: distances, Stars: variables: Cepheids, ISM: reflection nebulae, ISM: dust, extinction

1 INTRODUCTION

Westerlund (1961) discovered that the 41day Cepheid RS Pup was surrounded by a remarkable nebulosity. This is in the shape of rudimentary rings but with much distorted structure and condensations. Havlen (1972) showed that portions of the nebulosity varied in the period of the Cepheid but with various phase lags. A very beautiful set of measurements of phase lags at various points in the nebula has recently been obtained by Kervella et al. (2008) (= Kervella et al.). In general, the expected phase lag at a point i may be written:

$$(N_i + \Delta\phi_i) = 5.775510^{-3} D \theta_i (1 + \sin \alpha_i) / P \cos \alpha_i \quad (1)$$

Here $\Delta\phi_i$ is the fractional phase lag, N_i the whole number of pulsation periods elapsed, D is the distance to RS Pup in parsecs, θ_i is the angular distance of i from the star in arcsec, P is the pulsation period in days and α_i is the angle between the line joining the star to i and the plane of the sky (positive if i is further away than the star, negative if it is nearer). The measured quantities are $\Delta\phi_i$ and θ_i . P is assumed known and here it is taken as 41.4389 days (Kervella et al.). In an attempt to determine D , Kervella et al. assume $\alpha_i = \text{constant} = 0$. That is they assume that all the features measured by them lie in the plane of the sky and the values of N_i are then chosen to obtain the best fit to this model. The justification for this assumption is that if the nebulosity consisted of a series of thin, uniform, spherical shells centred on the star, then the deviation of all measured points from the plane of the sky would be small. However an examination of the structure of the nebulosity (for instance from the figures in Kervella et al.) shows that it is far from corresponding to this idealized model. There is much distortion and density variation in the rudimentary rings. Kervella et al. place special emphasis on the ten condensations or blobs shown in their fig 7. The existence of such blobs is not consis-

tent with the idealized model and leaves open the question of whether they or other features are actually in, or near, the plane of the sky. In view of these uncertainties it cannot be claimed that a definitive distance to RS Pup can be found based on the “in-the-plane” assumption. In the next section this assumption is dropped and it is shown that a simple and astrophysically interesting model for the nebulosity is found if a distance for RS Pup is adopted from a period-luminosity relation.

2 AN EQUATORIAL DISC MODEL

van Leeuwen et al. (2007) established a reddening-free period-luminosity relation in V, I based on HST (Benedict et al. 2007) and revised Hipparcos parallaxes. This together with the data in table A1 of that paper leads to a predicted distance of 1728pc for RS Pup¹. Adopting this distance it is possible to use eq. 1 to study the three dimensional structure of the nebulosity. In principle the values of N_i can be arbitrarily assigned. However they should obviously be chosen to account for apparent continuities in the structure and to conform to some simple, physically reasonable model. It was quickly found by trial and error that there is a consistent set of values of N_i in which the points measured by Kervella et al. are further away than the star on the south side and nearer on the north, i.e. an inclined disc model is indicated. This is indeed the simplest model, if the uniform spherical shell model is rejected. In such a model the values of N_i have to be chosen such that $(N_i + \Delta\phi_i)/\theta_i$ values are as near constant as possible in a given direction from the star and vary smoothly with direction. The details are given in

¹ The distance, 1830^{+109}_{-94} pc derived from the pulsational parallax by Fouqué et al. (2007) is not significantly different from this.

Table 1. This contains data on the 31 points observed by Kervella et al. and I am greatly indebted to them for supplying detail of their observations which were not given in the original paper. The Table lists:

1. Position number, i .
2. Angular distance from the star, θ_i , in arcsec.
3. Azimuth of the point relative to the star, β_i , measured from north through east, in degrees.
4. $\Delta\phi_i$ and its standard error.
5. The value of N_i ($= N_i^K$) adopted by Kervella et al. to fit their model assumptions.
6. The distance, d_y^K , behind (positive) or in front (negative) of the plane of the sky through the star. This is found by using eq.1 together with adopted values of N_i and D to derive α_i in each case. Then,

$$d_y = 4.848.10^{-2}\theta_i D \tan \alpha_i \quad (2)$$

where d_y is in units of 10^{-4} pc. For d_y^K the value of D estimated by Kervella et al. (1992 pc) was combined with their N_i^K values.

7. The value of N_i adopted in the present paper
8. The distance, d_y , behind or in front of the plane of the sky through the star assumed to be at its PL distance (1728pc) and adopting the revised values of N_i . The units are also in 10^{-4} pc.
9. The perpendicular distance d_x of the point from the intersection of the disc with the plane of the sky and projected onto the plane of the sky. In the same units as d_y . This is given by:

$$d_x = 83.77\theta_i \sin(\beta_i - \gamma) \quad (3)$$

where γ is the angle (azimuth) at which the plane of the disc cuts the plane of the sky. In this test of the model this is taken as close to the line from the star to point 9 (i.e. $\gamma = 80^\circ$). Fig. 1 shows a plot of d_x against d_y . This indicates a clear, apparently linear relation, between the two quantities. That is, the points lie in a tilted plane, presumably an equatorial disc. The line shown is a least squares fit through the origin and is given by:

$$d_y = 0.143(\pm 0.010)d_x \quad (4)$$

The tilt of the disc to the plane of the sky is $\tan^{-1} 0.143 = 8^\circ.1 \pm 0^\circ.6$. The rms scatter about the line in d_y is only 73.10^{-4} pc, much smaller than the diameter of the disc, which is $\sim 6800.10^{-4}$ pc out to the limits of the phase-lag survey. This rms scatter may be compared to the rms scatter of d_y^K which is 111.10^{-4} pc. No attempt has been made to optimize the disc model by, for instance, varying γ to find a better fit. This might reduce the rms scatter slightly. However this is already small compared to the diameter of the part of the disc surveyed indicating a relatively thin disc. A realistic disc will have some significant depth perpendicular to its axis and, indeed, Kervella et al. note that their observations at some positions suggest smoothing attributed to a non-zero depth in the line of sight. An inclined disc model broadly similar the one just discussed could probably be derived for other distances, if there were good evidence for these. However it should be noted that to take the distance as a free parameter in an attempt to reduce the rms scatter in the model is to assume that the disc must conform as closely as possible to an idealized model which is per-

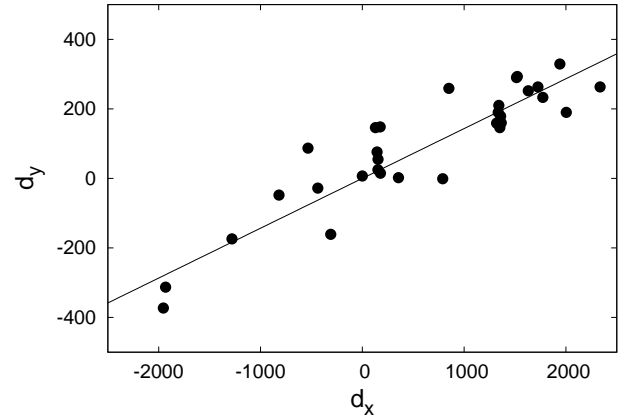


Figure 1. A plot of the distances, d_y , from the plane of the sky through the star against d_x the perpendicular distance, in the plane of the sky, to a line of azimuth $\gamma = 80^\circ$. The units are 10^{-4} pc. Note the expanded d_y scale.

fectly flat and of negligible thickness. There is no a priori justification for such an assumption.

An equatorial disc model for RS Pup is particularly interesting from the astrophysical point of view. Whilst it has seemed possible, for instance, that Cepheids might have ejected shells in a previous evolutionary phase, it has been puzzling that only for RS Pup is such a prominent structure found. The interpretation of the nebulosity as a disc at a small angle to the plane of the sky opens up the possibility of a deeper understanding of this phenomenon and its rarity. Obvious possibilities are loss of mass in the equatorial plane by unusually rapid rotation and/or binary interaction at an earlier evolutionary stage.

3 CONCLUSION

The structure seen in the RS Pup nebulosity makes questionable the assumption that phase-lag observations all refer to points close to the plane of the sky and this makes distance estimates based on this assumption questionable. An inclined disc model at a distance predicted by a period-luminosity relation gives a good fit to the data and opens new possibilities for understanding the system, including a possible interacting binary model.

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Table 1. The phase lag observations of Kervella et al. with derived linear positions

i	θ_i	β_i	$\Delta\phi_i \pm s.e.$	N_i^K	d_y^K	N_i	d_y	d_x
1	21.10	139	0.983 ± 0.020	5	43	5	290	1515
2	21.16	170	0.809 ± 0.012	5	-24	5	233	1773
3	21.65	196	0.989 ± 0.013	5	-7	5	252	1630
4	16.58	186	0.576 ± 0.009	4	-10	4	190	1335
5	16.03	167	0.504 ± 0.083	4	19	4	210	1341
6	12.89	213	0.102 ± 0.023	3	-179	3	-1	790
7	10.96	249	0.098 ± 0.023	3	19	3	148	175
8	29.28	312	0.207 ± 0.036	8	25	6	-313	-1933
9	19.42	80	0.697 ± 0.016	5	103	4	7	0
10	17.28	149	0.602 ± 0.014	4	-70	4	146	1351
11	11.03	252	0.108 ± 0.004	3	16	3	146	129
12	11.84	201	0.692 ± 0.010	3	133	3	259	850
13	16.26	166	0.462 ± 0.001	4	-17	4	179	1359
14	16.45	67	0.526 ± 0.001	4	-14	3	-161	-310
15	16.98	148	0.572 ± 0.033	4	-49	4	159	1319
16	17.04	187	0.589 ± 0.006	4	-49	4	160	1365
17	17.58	86	0.394 ± 0.009	4	-178	4	55	154
18	18.84	247	0.543 ± 0.005	5	108	4	2	355
19	20.59	170	0.770 ± 0.015	5	20	5	263	1725
20	20.99	140	0.965 ± 0.021	5	48	5	293	1523
21	24.43	255	0.925 ± 0.002	6	50	5	15	178
22	24.75	84	0.182 ± 0.025	6	-252	6	76	145
23	26.76	200	0.460 ± 0.003	7	12	7	329	1941
24	28.35	273	0.081 ± 0.004	7	-289	7	87	-534
25	28.74	156	0.717 ± 0.010	8	247	7	263	2336
26	29.61	312	0.138 ± 0.001	8	-27	6	-373	-1955
27	30.06	70	0.158 ± 0.015	8	-65	7	-28	-437
28	33.25	214	0.570 ± 0.055	9	117	8	190	2004
29	34.81	83	0.454 ± 0.006	9	-72	8	25	153
30	37.76	275	0.956 ± 0.004	10	163	8	-48	-819
31	39.14	283	0.938 ± 0.008	10	26	8	-174	-1281

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